CP Violation Beyond the Standard Model[1]

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Abstract

I review CP-violating signals of physics beyond the standard model in the B system. I examine the prospects for finding these effects at future colliders, with an emphasis on hadron machines.

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1   Introduction

I have been asked to review the various CP-violating signals for physics beyond the standard model (SM) in the B system, with a particular emphasis on future hadron colliders. Now, in any discussion of this type, one has to consider the following question: will this new physics (NP) be discovered directly or not? If the assumption is that the NP will not be observed directly at hadron colliders, then the aim of measuring CP violation in the B system is to find evidence for NP. This "discovery signal" study is model-independent. That is, if some signal is seen, one will know that NP is present, but one will not know what kind of NP it is. On the other hand, if one assumes that this NP can be produced directly at hadron colliders, then its discovery will also probably reveal its identity, though not the details of its properties. In this case, the study of B physics is still useful – it will furnish "diagnostic tests" of this NP. The point is that the future study of CP violation in the B system is important, though what we will learn depends on what is discovered (or not) through other measurements. In particular, it is essential to consider both possibilities — that the NP is discovered directly, or not — in any discussion of CP violation signals of NP at future colliders [1]. In this talk I will attempt to address both of these scenarios.

   If new physics exists, it can affect the B system in many different ways:

1. it can lead to new effects in B_s^0–$\bar{B}_s^0$ mixing or the $b \to s$ penguin amplitude, i.e. in the $b \to s$ flavour-changing neutral current (FCNC),

2. it can enter the $b \to d$ FCNC, i.e. B_d^0–$\bar{B}_d^0$ mixing or the $b \to d$ penguin,

3. it can affect tree-level decays, such as $b \to c\bar{q}q'$, $b \to u\bar{q}q'$, though this is less favoured theoretically.

Of course, any particular NP model may contain all of these effects, and all three classes of signals should be considered.

2   A Sign of New Physics?

As is well known, there is a hint of a discrepancy in CP violation in $B_d^0(t) \to \phi K_s$ – the Belle measurement of β from this mode disagrees with that obtained from $B_d^0(t) \to J/\psi K_s$, though there is no disagreement in the BaBar measurement [2]. If this discrepancy is confirmed, it would point to new physics in the $\bar{b} \to \bar{s}s\bar{s}$ penguin amplitude, i.e. in the $b \to s$ FCNC. Many models of NP have been proposed to explain this effect: Z- or Z'-mediated FCNC's, nonminimal supersymmetry (SUSY), SUSY with R-parity violation, left-right symmetric models, anomalous t-quark couplings, etc. [3]. If this effect is confirmed, we will want to distinguish among these models, either through other B-physics measurements, or through direct searches at hadron colliders.

This measurement raises an interesting question: is only the $\bar{b} \to \bar{s}s\bar{s}$ decay affected, or are all $b \to s$ FCNC amplitudes affected? For example, is there sizeable NP in B_s^0–$\bar{B}_s^0$ mixing? This question can be answered by making measurements of a variety of B decays.

One key task of hadron colliders is the measurement of B_s^0–$\bar{B}_s^0$ mixing. This is of great interest in any case, but the potential discrepancy in $B_d^0(t) \to \phi K_s$ only serves to emphasize its importance. In order to make this measurement, it will be necessary to resolve oscillations in the B_s system. Once it has been demonstrated that this is possible, one can turn to CP tests involving B_s^0 mesons.

Even if new physics is discovered directly, one cannot test the CP nature of the NP couplings to ordinary particles – this is the domain of B physics. Hadron colliders will make several important CP measurements involving B_s^0 mesons:

- Indirect CP violation in $B_s^0(t) \to D_s^+ D_s^-$, $J/\psi\phi$, $J/\psi\eta'$, etc. This measures the phase of B_s^0–$\bar{B}_s^0$ mixing, which is $\simeq 0$ in the SM.

- The measurement of $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to D_s^\pm K^\mp)$ probes γ in the SM [4]. In fact, this might possibly be the first direct measurement of this CP phase. Its value can be compared to that obtained from $\mathcal{A}_{CP}(B^\pm \to DK^\pm)$ at B-factories [5].

- Mixing-induced CP asymmetry in $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to \phi\phi)$. This decay is analogous to $B_d^0(t) \to \phi K_s$. Here, one will need to perform an angular analysis, discussed in more detail below. Within the SM, this CP asymmetry is expected to be $\simeq 0$.

In all cases, any discrepancy with the SM prediction points specifically to new physics, with new phases, in B_s^0–$\bar{B}_s^0$ mixing and/or the $b \to s$ penguin. (Note that not all models of NP predict new phases. For example, in the minimal supersymmetric SM with minimal flavour violation, there are no new phases — the couplings of all SUSY particles track the CKM matrix.)

As an aside, suppose that the phase of B_s^0–$\bar{B}_s^0$ mixing is measured in, say, $\mathcal{A}_{CP}^{mix}(B_s^0(t) \to \Psi\phi)$. The CKM phase $\chi \sim$ 2-5% is extracted. Within the SM [6],

$$\sin\chi = \left|\frac{V_{us}}{V_{ud}}\right|^2 \frac{\sin\beta\sin(\gamma - \chi)}{\sin(\beta + \gamma)} \ . \tag{1}$$

A discrepancy in this relation points to the presence of NP, though we can't pinpoint precisely where it enters.

3 Direct CP Violation

Other good tests for new physics involve direct CP asymmetries. Like any CP-violating signal, direct CP violation can only come about when there are two interfering amplitues. In this case, such CP violation corresponds to a difference in the

rate for a B decay process and its CP-conjugate. If a given decay has only a single amplitude, then the direct CP asymmetry must vanish.

There are many decays which are dominated by a single amplitude in the SM. Examples of these include $B \to J/\psi K$ and ϕK, $B_d^0 \to D_s^+ D^-$, $B_s^0 \to D_s^+ D_s^-$, $B_c^+ \to J/\psi \pi^+$, etc. If a direct CP asymmetry is measured in any of these modes, it implies the presence of NP in a penguin or tree amplitude. Note that many models of NP affect $b \to s$ or $b \to d$ penguin amplitudes; fewer affect tree amplitudes. A complete study of direct CP asymmetries will probe various NP models. If NP has already been found, this is a good way to study the new couplings.

One particularly useful decay is $B^+ \to \pi^+ K^0$. In the SM, we have $|A(B^+ \to \pi^+ K^0)| \simeq |A(B^- \to \pi^- \bar{K}^0)|$. Thus, any direct CP violation implies new physics, specifically in the $b \to s$ penguin. In this case the transition $\bar{b} \to \bar{s} d \bar{d}$ is affected. (Note that there is also a hint of NP in $B \to K\pi$ [2]. This is a good way of testing for this NP.)

4 Triple Products

One potential weakness of direct CP asymmetries is that

$$\mathcal{A}_{CP}^{dir} \propto \sin\phi \sin\delta \ , \tag{2}$$

where ϕ and δ are, respectively, the weak and strong phase differences between the SM and NP amplitudes. Thus, if $\delta = 0$, $\mathcal{A}_{CP}^{dir} = 0$, even if there is a NP contribution. This possibility can be addressed by measuring in addition triple-product correlations (TP's).

Triple product correlations take the form $\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3)$, where each v_i is a spin or momentum. TP's are odd under time reversal (T) and hence, by the CPT theorem, also constitute potential signals of CP violation. One can establish the presence of a nonzero TP by measuring a nonzero value of the asymmetry

$$A_T \equiv \frac{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) - \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)}{\Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) > 0) + \Gamma(\vec{v}_1 \cdot (\vec{v}_2 \times \vec{v}_3) < 0)} \ , \tag{3}$$

where Γ is the decay rate for the process in question.

The most obvious place to search for triple products is in the decay $B \to V_1 V_2$, where both V_1 and V_2 are vector mesons. In this case, the TP takes the form $\vec{\varepsilon}_1^{*T} \times \vec{\varepsilon}_2^{*T} \cdot \hat{p}$, where $\vec{p}$ is the momentum of one of the final vector mesons, and $\vec{\varepsilon}_1$ and $\vec{\varepsilon}_2$ are the polarizations of V_1 and V_2. Note that TP's can be obtained by performing an angular analysis of the $B \to V_1 V_2$ decay. However, as seen from Eq. (3), a full angular analysis is not necessary.

Now, because triple products are odd under T, they can be faked by strong phases. That is, one can obtain a TP signal even if the weak phases are zero. In order to obtain a true CP-violating signal, one has to compare the TP in $B \to V_1 V_2$

with that in $\bar{B} \to \bar{V}_1 \bar{V}_2$. The CP-violating TP is found by *adding* the two T-odd asymmetries [7]:

$$\mathcal{A}_T \equiv \frac{1}{2}(A_T + \bar{A}_T) \ . \tag{4}$$

Thus, neither tagging nor time dependence is necessary to measure TP's. One can in principle combine measurements of charged and neutral B decays [8].

The main point is that the CP-violating TP asymmetry of Eq. (4) takes the form

$$\mathcal{A}_T \propto \sin\phi \cos\delta \ . \tag{5}$$

That is, unlike $\mathcal{A}_{CP}^{dir}$ [Eq. (2)], the triple product does not vanish if $\delta = 0$. Thus, TP's are complementary to direct CP asymmetries. In order to completely test for the presence of NP, it is necessary to measure both direct CP violation and triple products.

This then begs the question: which $B \to V_1 V_2$ decays are expected to yield large TP's in the SM? Interestingly, the answer is *none* [7, 9, 10, 11]! It is straightforward to see how this comes about.

As noted above, all CP-violating effects require the interference of two amplitudes, with different weak phases. Thus, there can be no triple products in decays which in the SM are dominated by a single decay amplitude.

Now consider other $B \to V_1 V_2$ decays. Within factorization, the amplitude can be written

$$\sum_{\mathcal{O},\mathcal{O}'} \left\{ \langle V_1 | \mathcal{O} | 0 \rangle \langle V_2 | \mathcal{O}' | B \rangle + \langle V_2 | \mathcal{O} | 0 \rangle \langle V_1 | \mathcal{O}' | B \rangle \right\} \ , \tag{6}$$

where $\mathcal{O}$ and $\mathcal{O}'$ are SM operators. The key point is that TP's are a *kinematical* CP-violating effect [12]. That is, in order to produce a TP in a given decay, both of the above amplitudes must be present, with a relative weak phase.

For example, consider the decay $B_d^0 \to D^{*+} D^{*-}$. There is a tree amplitude, proportional to $V_{cb}^* V_{cd}$, and a penguin amplitude, proportional to $V_{tb}^* V_{td}$. Given that there are two amplitudes with a relative weak phase, one would guess that a CP-violating triple product would be produced. However, this is not the case. In fact, both amplitudes contribute to the $\langle D^{*+} | \mathcal{O} | 0 \rangle \langle D^{*-} | \mathcal{O}' | B \rangle$ matrix elements; there is no $\langle D^{*-} | \mathcal{O} | 0 \rangle \langle D^{*+} | \mathcal{O}' | B \rangle$. (That is, in the SM one has only $\bar{b} \to \bar{c}$ transitions; $\bar{b} \to c$ transitions do not occur.) Thus, despite the presence of two amplitudes in this decay, no TP is produced, at least within factorization.

Using the above argument, we note that there are three classes of $B \to V_1 V_2$ decays in the SM, all of which are expected to have zero or small triple products:

1. Decays governed by a single weak decay amplitude, such as $B \to J/\psi K^*$, $B_s^0 \to \phi\phi$, $B_s^0 \to D_s^* D_s^*$, $B_c^+ \to J/\psi \rho^+$, etc. Because there is only one amplitude, there can be no CP-violating effects, including TP's. This is model-independent.

2. Color-allowed decays with two weak decay amplitudes, such as $\bar{B}_d^0 \to D^{*+}D^{*-}$, $\bar{B}_s^0 \to D_s^{*+}D^{*-}$, $\bar{B}_s^0 \to K^{*+}K^{*-}$, $B_c^- \to \bar{D}^{*0}\rho^-$, $B_c^- \to \bar{D}^{*0}K^{*-}$, etc. The two amplitudes are usually a tree and a penguin diagram, though it is possible to have two penguin contributions. As argued above, both decay amplitudes contribute to the same kinematical amplitude, so that all TP's vanish. Since the decays are colour-allowed, nonfactorizable corrections are expected to be small, so that the prediction of tiny TP's is robust.

3. Color-suppressed decays with two weak amplitudes, such as $B^- \to \rho^0 K^{*-}$, $\bar{B}_s^0 \to \phi K^*$, $B_c^- \to J/\psi D^{*-}$, etc. Once again, within factorization, both amplitudes contribute to the same kinematical amplitude, so that the TP's vanish. However, nonfactorizable effects may be large in colour-suppressed decays. We have tried to be conservative in our estimates of such effects, and still find tiny TP's for such decays [11]. This conclusion is clearly model-dependent. (In any case, the branching ratios for such decays are very small.)

The fact that all TP's in $B \to V_1 V_2$ are expected to vanish or be very small in the SM makes this an excellent class of measurements to search for new physics. In the SM, all couplings to the b-quark [i.e. the operators $\mathcal{O}'$ in Eq. (6)] are left-handed. Within factorization, the discovery of a large TP in a $B \to V_1 V_2$ decay would point to new physics with large couplings to the right-handed b-quark [10, 11]. Many new-physics models, though not all, have such couplings. As an example, supersymmetry with R-parity-violating couplings can explain the apparent discrepancy in $B_d^0(t) \to \phi K_s$. Such a model of NP will also contribute to $B \to \phi K^*$ decays, leading to TP's. In the SM, such TP's vanish; with this type of NP, one can get TP asymmetries as large as 15–20% [11]! The upshot is that triple products are excellent diagnostic tests for new physics. Some NP models predict large TP's, so that null measurements can strongly constrain (or eliminate) such models.

5   Time-Dependent Angular Analysis

Consider now a $V_1 V_2$ state which in the SM is dominated by a single amplitude. Suppose that there is a new-physics amplitude, with a different weak phase, contributing to this decay. Above, I have argued that one can detect such an amplitude by looking for both direct CP violation and triple products. However, much more information can be obtained if a time-dependent angular analysis of the corresponding $B^0(t) \to V_1 V_2$ decay can be performed [8].

The time-dependent decay rate for $B^0(t) \to V_1 V_2$ is given by

$$\Gamma(B^0(t) \to V_1 V_2) = e^{-\Gamma t} \sum_{\lambda \leq \sigma} \left(\Lambda_{\lambda\sigma} + \Sigma_{\lambda\sigma} \cos(\Delta M t) - \rho_{\lambda\sigma} \sin(\Delta M t) \right) g_\lambda g_\sigma \ . \quad (7)$$

In the above, the helicity indices λ and σ take the values $\{0, \|, \perp\}$, and the g_λ are known functions of the kinematic angles. For a given helicity λ, $\Lambda_{\lambda\lambda}$ essentially

measures the total rate, while $\Sigma_{\lambda\lambda}$ and $\rho_{\lambda\lambda}$ represent the direct and indirect CP asymmetries, respectively. The quantity $\Lambda_{\perp i}$ $(i = \{0, \|\})$ is simply the triple product discussed earlier.

Now, there are 18 observables in this decay rate. However, if there is no new physics, there are only 6 theoretical parameters. This implies that there are 12 relations among the observables. They are:

$$\Sigma_{\lambda\lambda} = \Lambda_{\perp i} = \Sigma_{\|0} = 0 \ ,$$
$$\rho_{ii}/\Lambda_{ii} = -\rho_{\perp\perp}/\Lambda_{\perp\perp} = \rho_{\|0}/\Lambda_{\|0} \ ,$$
$$2\Lambda_{\|0}\Lambda_{\perp\perp}\left(\Lambda_{\lambda\lambda}^2 - \rho_{\lambda\lambda}^2\right) = \left[\Lambda_{\lambda\lambda}^2\rho_{\perp 0}\rho_{\perp\|} + \Sigma_{\perp 0}\Sigma_{\perp\|}\left(\Lambda_{\lambda\lambda}^2 - \rho_{\lambda\lambda}^2\right)\right] \ ,$$
$$\rho_{\perp i}^2\Lambda_{\perp\perp}^2 = \left(\Lambda_{\perp\perp}^2 - \rho_{\perp\perp}^2\right)\left(4\Lambda_{\perp\perp}\Lambda_{ii} - \Sigma_{\perp i}^2\right) \ . \tag{8}$$

The violation of any of these relations will be a smoking-gun signal of NP. If the NP conspires to make direct CP violation and TP's small, it can still be detected through one of these other signals [8]. Thus, if a time-dependent angular analysis can be performed, there are many more ways to search for new physics.

However, even more can be done! Suppose that some signal for new physics is found. In this case, it is straightforward to show that there are more theoretical parameters than independent observables, so that one cannot solve for the NP parameters. However, because the expressions relating the observables to the theoretical parameters are nonlinear, one can actually put a *lower bound* on the NP parameters [8]. This is extremely important, as it allows us to get direct information on the NP through measurements in the B system.

6 α from $B^0 \to K^{(*)}\bar{K}^{(*)}$ Decays

I now turn to the extraction of α from $B^0_{d,s} \to K^{(*)}\bar{K}^{(*)}$ decays [13]. Consider first $B^0_d \to K^0\bar{K}^0$, which is a pure $b \to d$ penguin:

$$\begin{aligned} A(B^0_d \to K^0\bar{K}^0) &= P_u V_{ub}^* V_{ud} + P_c V_{cb}^* V_{cd} + P_t V_{tb}^* V_{td} \\ &= \mathcal{P}_{uc}\, e^{i\gamma}\, e^{i\delta_{uc}} + \mathcal{P}_{tc}\, e^{-i\beta}\, e^{i\delta_{tc}} \ , \end{aligned} \tag{9}$$

where $\mathcal{P}_{uc} \equiv |(P_u - P_c)V_{ub}^* V_{ud}|$, $\mathcal{P}_{tc} \equiv |(P_t - P_c)V_{tb}^* V_{td}|$, and I have explicitly written out the strong phases δ_{uc} and δ_{tc}, as well as the weak phases β and γ. By measuring $B^0_d(t) \to K^0\bar{K}^0$, one can extract 3 observables – the total rate, and the direct and indirect CP asymmetries. However, these depend on the 4 unknowns $\mathcal{P}_{uc}$, $\mathcal{P}_{tc}$, $\Delta \equiv \delta_{uc} - \delta_{tc}$ and α, so that CP phase information cannot be obtained.

Now consider a second pure $b \to d$ penguin decay of the form $B^0_d \to K^*\bar{K}^*$, where K^* represents any excited neutral kaon. This decay can be treated completely analogously to $B^0_d \to K^0\bar{K}^0$, with unprimed parameters and observables being replaced by ones with tildes. The measurement of the time-dependent rate again allows one

to extract 3 observables, which depend on the 4 unknowns $\widetilde{\mathcal{P}}_{uc}$, $\widetilde{\mathcal{P}}_{tc}$, $\widetilde{\Delta}$ and α. Again, there are more observables than unknowns, so that one cannot extract α. However, one can combine measurements from the two decays to write

$$\frac{\mathcal{P}_{tc}^2}{\widetilde{\mathcal{P}}_{tc}^2} = f(\alpha, \text{observables}) . \tag{10}$$

Note that the CKM matrix elements $|V_{tb}^* V_{td}|$ cancel in this ratio. From this ratio, we see that we could solve for α if we knew the value of $\mathcal{P}_{tc}/\widetilde{\mathcal{P}}_{tc}$.

This information can be obtained by considering $B_s^0 \to K^{(*)} \bar{K}^{(*)}$ decays. Consider the decay $B_s^0 \to K^0 \bar{K}^0$, which is a pure $b \to s$ penguin:

$$\begin{aligned}
A(B_s^0 \to K^0 \bar{K}^0) &= P_u' V_{ub}^* V_{us} + P_c' V_{cb}^* V_{cs} + P_t' V_{tb}^* V_{ts} \\
&= \mathcal{P}_{uc}' e^{i\gamma} e^{i\delta_{uc}'} + \mathcal{P}_{tc}' e^{i\delta_{tc}'} \\
&\simeq \mathcal{P}_{tc}' e^{i\delta_{tc}'} .
\end{aligned} \tag{11}$$

Here $\mathcal{P}_{uc}' \equiv |(P_u' - P_c')V_{ub}^* V_{us}|$ and $\mathcal{P}_{tc}' \equiv |(P_t' - P_c')V_{tb}^* V_{ts}|$. However, $|V_{ub}^* V_{us}/V_{tb}^* V_{ts}| \simeq 2\%$, so that the u-quark piece $\mathcal{P}_{uc}'$ is negligible compared to $\mathcal{P}_{tc}'$, leading to the last line above. Therefore the measurement of $B(B_s^0 \to K^0 \bar{K}^0)$ gives $\mathcal{P}_{tc}'$. Similarly, the measurement of $B(B_s^0 \to K^* \bar{K}^*)$ gives $\widetilde{\mathcal{P}}_{tc}'$.

The key point is that, in the flavour SU(3) limit, we have $\mathcal{P}_{tc}'/\widetilde{\mathcal{P}}_{tc}' = \mathcal{P}_{tc}/\widetilde{\mathcal{P}}_{tc}$. Thus, using Eq. (10), one can obtain α. Now, uncertainties due to SU(3) breaking are typically $\sim 25\%$. However, these leading-order effects *cancel* in the double ratio $(\mathcal{P}_{tc}'/\widetilde{\mathcal{P}}_{tc}')/(\mathcal{P}_{tc}/\widetilde{\mathcal{P}}_{tc})$. One is left with only second-order SU(3)-breaking effects, i.e. a theoretical error of at most 5% [13].

One can compare the value of α extracted with this method with that obtained elsewhere (e.g. in $B \to \pi\pi$ or $B \to \rho\pi$). A discrepancy would point to new physics in the $b \to d$ or $b \to s$ penguin.

It is useful to list some experimental considerations. First, B_s^0 mesons are involved, and all branching ratios are $\sim 10^{-6}$. Second, the $K^{(*)}$ and $\bar{K}^{(*)}$ mesons are detected through their decays to charged π's and K's only, requiring good K/π separation. Finally, no π^0 detection needed. All in all, this method is particularly appropriate to hadron colliders.

7   Triple products in Λ_b Decays

Another class of decays which can only be studied at hadron colliders are those involving Λ_b baryons. Consider the decays $\Lambda_b \to F_1 P$ and $F_1 V$, where F_1 is a fermion (p, Λ, ...), P is a pseudoscalar (K^-, η, ...), and V is a vector (K^{*-}, ϕ, ...). In these decays, triple products are possible [14]. In $\Lambda_b \to F_1 P$, only one TP is possible: $\vec{p}_{F_1} \cdot (\vec{s}_{F_1} \times \vec{s}_{\Lambda_b})$, where $\vec{s}_i$ is the spin of particle i. On the other hand, since

the decay $\Lambda_b \to F_1 V$ involves three spins and one final momentum, four TP's are possible.

As in $B \to V_1 V_2$ decays, within factorization we require a right-handed coupling to b-quarks in order to generate a TP. For certain $F_1 P$ final states, one can "grow" a sizeable right-handed current due to the Fierz transformations of some of the SM operators. However, for $F_1 V$ final states, there are no such right-handed currents. Thus, all TP's are expected to vanish in the SM for $\Lambda_b \to F_1 V$ decays.

We find that $\mathcal{A}_T^{pK} = -18\%$, but the TP's for all other fermion-pseudoscalar final states (pK^{*-}, $\Lambda\eta$, $\Lambda\eta'$, $\Lambda\phi$) are small, at most $O(1\%)$. Once again, the fact that almost all TP's are expected to be small implies that this is a good place to look for new physics. In fact, one can use TP's in Λ_b decays as a diagnostic tool for NP [15].

8   Radiative Decays

Finally, I consider radiative decays of B mesons. The inclusive partial rate asymmetries can be calculated reliably in the SM [16]:

$$
\begin{aligned}
\mathcal{A}_{CP}^{dir}(b \to s\gamma) &= 0.5\% ,\\
\mathcal{A}_{CP}^{dir}(b \to d\gamma) &= -10\% .
\end{aligned}
\tag{12}
$$

If measurements of these asymmetries are found to differ from their SM values, this will indicate the presence of new physics. Indeed, large deviations are possible in several models of NP [17].

Exclusive partial rate asymmetries in $B \to K^*\gamma$ and $B \to \rho\gamma$ are not known as well – there are important bound-state corrections [18]. However, if significant deviations from the values calculated for inclusive decays are found in exclusive decays, this probably points to new physics.

One can also consider mixing-induced CP asymmetries (e.g. $B_d^0(t) \to \rho\gamma$, $B_s^0(t) \to \phi\gamma$). In the SM the photon polarization is opposite for B and $\bar{B}$ decays, so that no interference is possible. That is, $\mathcal{A}_{CP}^{mix}(b \to s\gamma, b \to d\gamma) \simeq 0$ in the SM. However, one can get a significant $\mathcal{A}_{CP}^{mix}$ in certain models of NP (e.g. left-right symmetric models, SUSY, models with exotic fermions) [19].

9   Conclusion

In summary, there are numerous signals of new physics in B and Λ_b decays. Furthermore, there are many ways of determining which types of NP might be responsible for these signals. If the NP is discovered directly, the measurement of CP violation in the B system can be used to probe its couplings. Thus, the study of B processes is complementary to direct searches for NP. Hadron colliders have a significant role to play in the discovery of NP, as well as in its identification.

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